PERSPECTIVE

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The mystery of recent stratospheric temperature trends

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A new data set of middle- and upper-stratospheric temperatures based on reprocessing of satellite radiances provides a view of stratospheric climate change during the period 1979–2005 that is strikingly different from that provided by earlier data sets. The new data call into question our understanding of observed stratospheric temperature trends and our ability to test simulations of the stratospheric response to emissions of greenhouse gases and ozone-depleting substances. Here we highlight the important issues raised by the new data and suggest how the climate science community can resolve them.

The radiative effects of human emissions of ozone-depleting substances and greenhouse gases have driven marked atmospheric cooling at stratospheric altitudes[1–5]. Ozone depletion is believed to have caused the preponderance of the cooling in the lower stratosphere (around 15–25 km altitude); both ozone depletion and increases in greenhouse gases are believed to have driven the cooling in the middle and upper stratosphere (around 25–50 km altitude)[2]. Stratospheric temperature trends play an important part in allowing us to distinguish between the climate responses to natural and anthropogenic climate forcings[6]. Although less widely discussed in either scientific or policy circles, stratospheric cooling is as fundamental as surface warming as evidence of the influence of anthropogenic emissions on the climate system.

Unfortunately, observations of stratospheric temperatures are limited. The surface temperature record extends for over a century and is derived from multiple data sources[7]. In contrast, the stratospheric temperature record spans only a few decades and is derived from a handful of data sources[3,4]. Radiosonde (weather balloon) measurements are available in the lower stratosphere but do not extend to the middle and upper stratosphere[3,8]. Lidar (light detection and ranging) measurements extend to the middle and upper stratosphere but have very limited spatial and temporal sampling[3,9]. By far the most abundant observations of long-term stratospheric temperatures are derived from satellite measurements of long-wave radiation emitted by Earth's atmosphere.

The longest-running records of remotely sensed stratospheric temperatures are provided by the Microwave Sounding Unit (MSU), the Advanced Microwave Sounding Unit (AMSU), and the Stratospheric Sounding Unit (SSU). The SSU and MSU instruments were flown onboard a consecutive series of seven NOAA polar-orbiting satellites that partially overlap in time from late 1978 to 2006; the AMSU instruments have been flown onboard NOAA satellites from mid-1998 to the present day[3].

The MSU, AMSU and SSU temperature measurements do not represent temperatures at discrete height levels, but rather are representative of temperatures averaged over a continuum of altitudes described by the appropriate instrument 'weighting functions' (see, for example, Figure 2 in ref. 4). The weighting function for the highest available MSU channel (MSU channel 4) peaks in the lower stratosphere near 20 km altitude. The weighting functions for the SSU instrument peak in the middle and upper stratosphere at 25–35 km (SSU channel 1), 35–45 km (SSU channel 2), and 40–50 km (SSU channel 3).

Continuous time series of lower-stratospheric temperatures are derived by combining measurements from satellites that carried MSU instruments from 1978–2005 and AMSU instruments from 1998 to the present[3]. The lower-stratospheric MSU and AMSU data have been processed and combined by three different research groups: Remote Sensing Systems (RSS)[10], the University of Alabama-Hunstville (UAH)[11], and the NOAA Center for Satellite Applications and Research (STAR)[12]. The processing methodologies and resulting lower-stratospheric temperature data have been published extensively in the peer-reviewed literature[3,4].

Global-mean lower-stratospheric temperatures derived from the three primary stratospheric MSU products are very similar to each other (red, purple and green lines in Fig. 1d (the red, purple and green lines in Fig. 1d are reproduced in Fig. 1h to facilitate comparison with model simulations, as discussed below); the large but short-lived warmings starting in 1982 and 1991 are due to the volcanic eruptions of El Chichón and Mount Pinatubo, respectively). They are also very similar to lower-stratospheric temperatures estimated from radiosonde data[3,4]. The differences among the three MSU lower-stratospheric global-mean temperature time series are larger than those associated with separate estimates of global-mean surface temperatures[4]. And yet the differences between the MSU time series pale in comparison with those associated with the primary SSU products, as demonstrated below.

The mystery

Conflicting evidence

Continuous time series of temperatures in the middle and upper stratosphere back to 1979 are based exclusively on SSU data (the AMSU data also sample the middle and upper stratosphere but are available only since 1998). The SSU data require correction for several unique issues before they can be used for climate studies (see discussion in ref. 4). For example, (1) the SSU instrument relies critically on a cell pressure modulator of carbon dioxide to determine the emission of stratospheric radiation from different altitudes. The cells in all SSU instruments leaked with time, causing changes in the altitudes being measured; (2) the amplitude of the atmospheric thermal tides—and thus the tidal corrections between successive satellite missions—is relatively large in the middle and upper stratosphere; (3) long-term increases in atmospheric carbon dioxide influence the weighting function of the instrument; and (4) there is no overlap period between several pairs of consecutive satellites.

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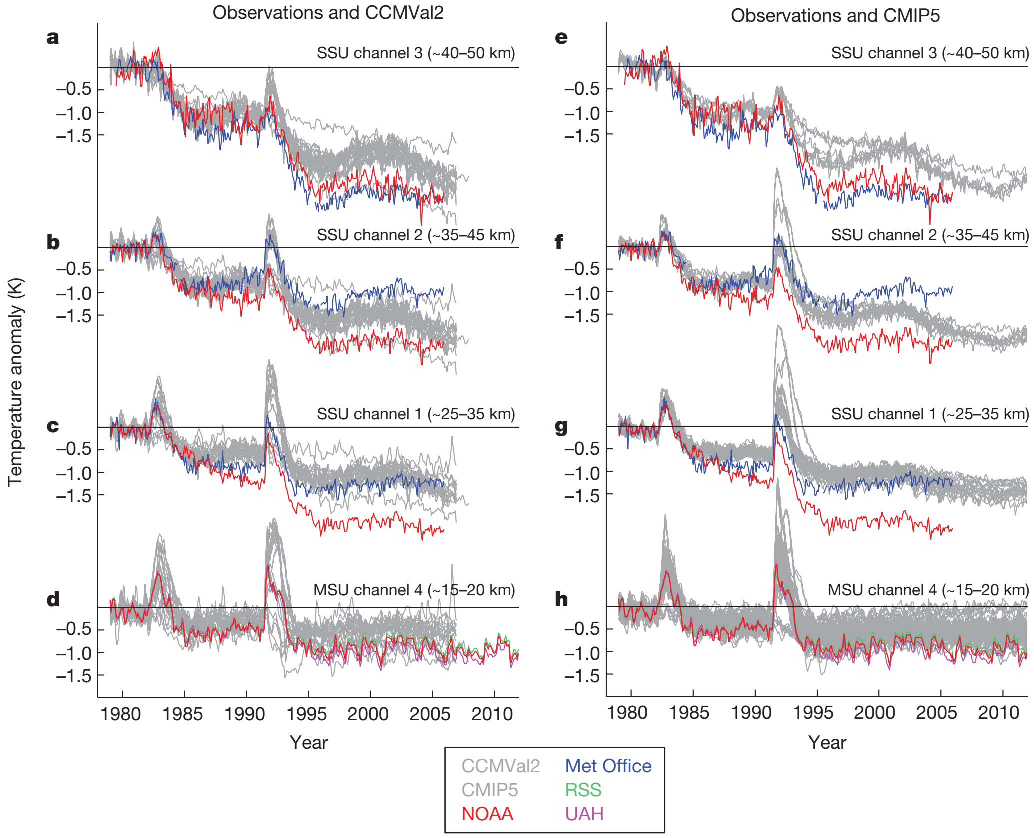

Figure 1 | Global-mean stratospheric temperature anomalies since 1979. Time series of monthly mean, global-mean stratospheric temperature anomalies are shown for the altitude ranges, data sets and model output indicated. Red, blue, green and purple lines indicate results based on observations (observations are reproduced in the left and right panels). **a**–**h**, Grey lines indicate results from the coupled CCM runs available through the CCMVal2 archive (**a**–**d**) and from the AOGCM runs available through the CMIP5 archive (**e**–**h**). Model runs are listed in Table 1 and were converted to SSU and MSU time series using the appropriate instrument weighting functions[9,15]. Time series are plotted so that their 1979–1982 mean anomalies are zero. Note that several CMIP5 models have poor vertical resolution at middle and upper stratospheric altitudes. For this reason, more model simulations are available at lower than at upper stratospheric levels (see Table 1).

The SSU data were originally processed for climate analysis by scientists at the UK Met Office in the 1980s[13,14]. The data were further revised in 2008 to account for variations in the satellite weighting functions over time due to changes in atmospheric composition[15]. However, the methodology used to develop the Met Office SSU product was never published in the peer-reviewed literature, and certain aspects of the original processing remain unknown. For this reason, the NOAA STAR recently reprocessed the SSU temperatures and published the full processing methodology and the resulting data in the peer-reviewed literature[16].

The new NOAA SSU data provide an invaluable independent resource for assessing the reproducibility of the original Met Office SSU data. But the new data raise more questions than they answer, because they provide a strikingly different view of recent stratospheric temperature trends (compare the red and blue lines in Fig. 1a–c; the red and blue lines in Fig. 1a–c are reproduced in Fig. 1e–g to facilitate comparison with model simulations, as discussed below). The long-term variability and trends in global-mean temperatures for the uppermost SSU channel (SSU channel 3) are relatively similar in both the Met Office and NOAA data sets. But the same cannot be said for the SSU channels that sample the middle stratosphere (SSU channels 1 and 2). The global-mean cooling in channels 1 and 2 (around 25–45 km) is nearly twice as large in the NOAA data set as it is in the Met Office data set (Figs 1 and 2)[16]. The differences between the NOAA and Met Office channels 1 and 2 global-mean time series do not arise from a discrete period of time, but rather increase from about 1985 to the end of the record[16]. The differences between the NOAA and Met Office global-mean time series shown in Fig. 1 are so large they call into question our fundamental understanding of observed temperature trends in the middle and upper stratosphere.

Disconnects between observations and models

The story is further muddled when the observations are compared with attempts to simulate the past few decades of stratospheric climate change using climate models. Two classes of climate models commonly used in simulations of past climate are coupled chemistry–climate models (CCMs) and coupled atmosphere–ocean global climate models (AOGCMs). By definition, the CCMs explicitly simulate stratospheric chemical processes, whereas the AOGCMs explicitly simulate coupled atmosphere–ocean interactions. In principle, a coupled chemistry–climate model might also simulate coupled atmosphere–ocean interactions, and vice versa. But owing to computational limitations, most current CCMs are not AOGCMs, and vice versa. A key distinction between the model classes that is pertinent to this discussion is that in general the CCMs resolve the stratosphere more fully than do the AOGCMs.

Simulations from CCMs forced with the time history of anthropogenic emissions are available via the CCM validation activity (Figs 1a–d and 2a–d, results are from the CCMVal2 project; see Table 1 and ref. 17). Between 40 and 50 km (channel 3), global-mean temperature trends from both SSU products show more cooling than is simulated by the CCMs (Figs 1a and 2a; the model temperatures are weighted by the appropriate satellite weighting functions). Between about 35 and 45 km (channel 2), the Met Office version of the SSU data suggests that the models overestimate the observed stratospheric cooling, whereas the NOAA SSU data suggest that the models underestimate it (Figs 1b and 2b). The most striking discrepancies are between about 25 and 35 km (channel 1; Figs 1c and 2c). As demonstrated in refs 4 and 18, the Met Office SSU data are in reasonable agreement with the current generation of coupled CCMs at these altitudes. But as shown in Figs 1a–d and 2a–d, the cooling

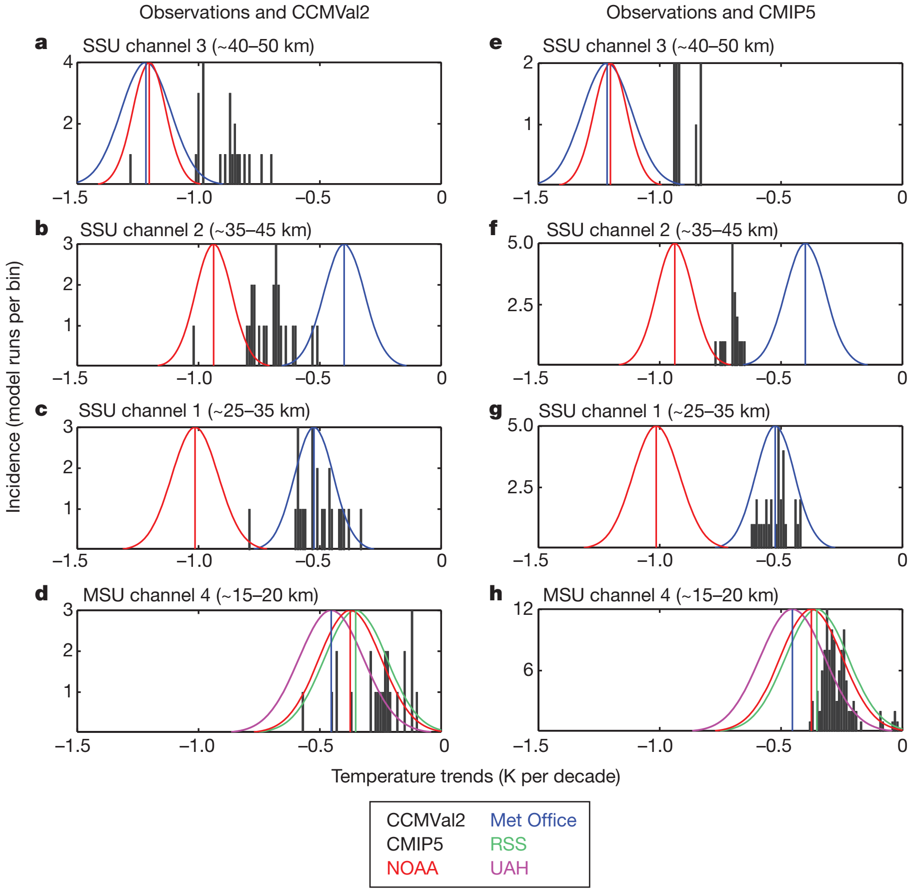

Figure 2 | Trends in global-mean stratospheric temperatures between 1979 and 2005. Trends in monthly mean, global-mean stratospheric temperatures are shown for the altitude ranges, data sets and model output indicated. Observed trends are denoted by the red, blue, green and purple vertical lines (observed trends are reproduced in the left and right panels). The normalized red, blue, green and purple probability distribution functions indicate the confidence ranges on the trend estimates, taking into account the effective number of degrees of freedom in the respective time series (for example, the 95% confidence bounds correspond to the edges of the area that spans the middle 95% of the distribution function). **a–h**, Black bars show the histograms of the trends from the CCM runs available through the CCMVal2 archive (**a**–**d**) and from the AOGCM runs available through the CMIP5 archive (**e**–**h**). Each temperature trend bin is 0.01 K per decade wide. The total number of model runs is given in Table 1.

in the new NOAA SSU channel 1 data is nearly twice as large as the cooling simulated by most of the CCMs.

A similar story emerges when observations of global-mean stratospheric temperature are compared with the simulations of AOGCMs prepared for the upcoming IPCC Fifth Assessment Report (Figs 1e–h and 2e–h; results are from the Coupled Model Intercomparison Project Phase 5 simulations, CMIP5; see Table 1). Most of the CMIP5 models are not coupled CCMs and have considerably less vertical resolution at stratospheric altitudes than the models archived by CCMVal2. For this reason, relatively few CMIP5 model runs include altitudes sampled by SSU channels 2 and 3.

The differences between the CMIP5 models and the observations are comparable to those noted in association with the CCMVal2 models in all SSU channels (Figs 1e–h and 2e–h). The CMIP5 models indicate considerably less cooling than both SSU products at about 40–50 km (channel 3); lie between the two SSU products at about 35–45 km (channel 2); and provide a closer fit to the Met Office SSU data than the NOAA SSU data at about 25–35 km (channel 1).

It is possible that the models are correct and that both SSU data sets are in error. But the CCMs and AOGCMs also exhibit smaller yet systematic discrepancies with observations in the lower stratosphere, which is sampled by the MSU channel 4 instrument (Figs 1d, h and 2d, h). With few exceptions, the models underestimate the amplitude of the long-term cooling in the lower stratosphere (Figs 1d, h and 2d, h) and have difficulty simulating the amplitude of the response to the eruptions of El Chichón and Mount Pinatubo there (Fig. 1d, h). Previous studies have reported close agreement between trends in the MSU channel 4 data and in CCMVal2 simulations[18], but those trend comparisons were done between observations of MSU channel 4 temperature and model output at specific height levels (that is, the model trends were shown as a function of height and not averaged over the MSU channel 4 weighting function; see figure 2 in ref. 18, for example).

The latitudinal profiles of the trends from the different SSU data sources are also remarkably different from those simulated by the current generation of CCMs (Fig. 3). The Met Office SSU data suggest that the cooling of the past few decades was relatively uniform with latitude (blue lines in Fig. 3a–c). In contrast, the NOAA SSU data suggest that the largest stratospheric cooling occurred at tropical latitudes, particularly between 25 km and 45 km (red lines in Fig. 3a–c). The differences between the Met Office and NOAA global-mean stratospheric temperature trends clearly derive primarily from tropical latitudes. The tropical stratospheric cooling indicated by the models is noticeably weaker than that indicated by the NOAA SSU data in the middle and upper stratosphere (Fig. 3a–c), and is generally weaker than that indicated by all MSU channel 4 products in the lower tropical stratosphere (Fig. 3d).

What might cause cooling in the tropical stratosphere? The radiative effects of increasing carbon dioxide are modest below 40 km altitude[2]. Rather, at altitudes sampled by SSU channel 1, long-term tropical cooling is most likely to result from either anomalous rising motion, which decreases air temperature through expansion, or *in situ* ozone depletion, which decreases temperature by reducing the absorption of short-wave radiation. The two processes are closely related: rising motion leads to

Table 1 | Model runs used in this study

CMIP5 model runs	CCMVal2 model runs
CanESM2* (5)	AMTRAC3
CCSM4 (6)	CCSRNIES
CSIRO-Mk3.6.0 (10)	CMAM (3)
FGOALS-s2 (3)	EMAC
GFDL-CM3* (5)	LMDZrepro (3)
GFDL-ESM2G (1)	MRI (4)
GFDL-ESM2M (1)	NIWA SOCOL
GISS-E2-H (15)	SOCOL (3)
GISS-E2-R (16)	ULAQ
HadCM3 (10)	UMSLIMCAT
HadGEM2-CC** (3)	WACCM (4)
HadGEM2-ES (4)	
INMCM4 (1)	
IPSL-CM5A-LR (5)	
IPSL-CM5A-MR (1)	
IPSL-CM5B-LR (1)	
MIROC4h* (3)	
MIROC5 (4)	
MIROC-ESM*** (3)	
MIROC-ESM-CHEM*** (1)	
MPI-ESM-LR*** (3)	
MPI-ESM-P*** (2)	
MRI-CGCM3** (5)	
NorESM1-M (3)	
NorESM1-ME (1)	

Numbers in parentheses indicate the number of ensemble members. The number of asterisks indicates at which level the model temperature data was used based on which levels are available in model output. No asterisks means used only in MSU channel 4 (any model with no output at 1 hPa). *Used in MSU channel 4 and SSU channel 1 (any model with output at 1 hPa). **Used in MSU channel 4, SSU channels 1 and 2 (any model with output at pressures below 1 hPa). ***Used in all channels (any model with output at pressures below 0.1 hPa). Model nomenclature is provided in ref. 17 and the IPCC Fifth Assessment Report (http://www.ipcc.ch/).

decreases in ozone in the lower stratosphere through the vertical transport of low-ozone air from lower altitudes. The two processes are also both potentially implicated in recent stratospheric climate change.

Rising motion in the tropical stratosphere occurs as part of the large-scale, equator-to-pole stratospheric mass circulation. Most coupled CCMs suggest that increasing greenhouse gases accelerate the stratospheric mass circulation[19–24]. Such an acceleration is expected to be marked by decreases in tropical stratospheric ozone and temperatures (particularly in the lower stratosphere), and observations suggest that both changes are occurring. Ground-based and satellite measurements suggest that tropical lower-stratospheric ozone has decreased over the past few decades at a rate comparable to that predicted by the CCMs[25,26], radiosonde data suggest that tropical lower-stratospheric temperatures have decreased since 1979[3,27–29] and the NOAA SSU data suggest that such tropical cooling extends to the middle and upper stratosphere (Fig. 3). (In principle, the acceleration of the mass circulation should also be marked by increases in temperatures and ozone concentrations in the extratropical stratosphere owing to the anomalous downward motion there, but the effects of the mass circulation at extratropical latitudes are opposed by the effects of polar stratospheric chemical ozone depletion in the Southern Hemisphere—the ‘Antarctic ozone hole’—and masked by naturally high levels of year-to-year climate variability in the Northern Hemisphere.)

If the new NOAA SSU data are correct, they suggest that the stratospheric mass circulation is accelerating at a rate considerably higher than that predicted by the CCMs, at least in the middle and upper stratosphere (that is, at the altitudes sampled by the SSU instrument). Again, it is possible that the models are correct and that the SSU data are in error. But the fact that the discrepancies between the magnitudes of the simulated and observed cooling in the tropical stratosphere extend to MSU channel 4, which samples the lower stratosphere and exhibits trends that are fairly reproducible from one data set to the next (Figs 1d, h, 2d, h and 3d), suggest that model uncertainties should not be discounted.

Moving forward to resolve the mystery

Are the models missing a key aspect of stratospheric climate change? Or is there an error in the newly processed NOAA data? Which SSU data set is correct? Or are both in error?

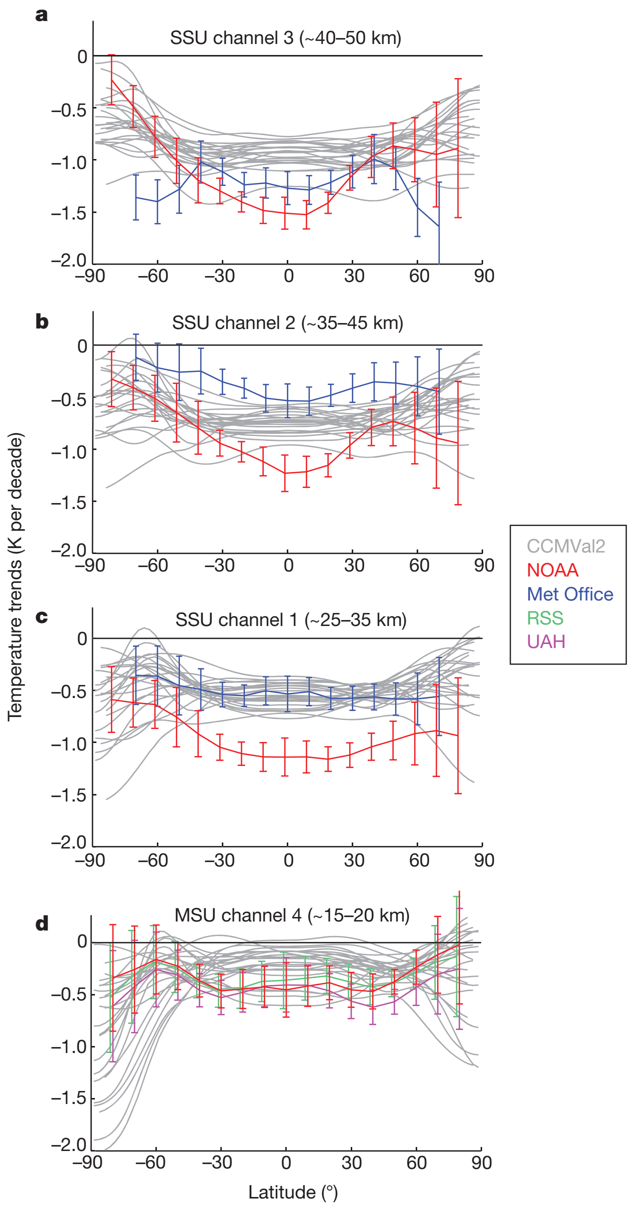

Figure 3 | The north–south structure of zonal-mean stratospheric temperature trends between 1979 and 2005. a–d, Trends in monthly mean, zonal-mean stratospheric temperatures are shown for the altitude ranges, data sets and model output indicated. Error bars approximate the 95% confidence bounds.

The latitudinal structure of stratospheric temperature trends is influenced by both radiative processes and variability in the stratospheric mass circulation. As noted above, the predicted acceleration of the stratospheric mass circulation[19–24] should lead to enhanced stratospheric cooling at tropical latitudes, and such cooling is found in the middle and upper stratosphere in both the NOAA SSU data and the CCMVal2 simulations (Fig. 3). However, the magnitudes of the predicted acceleration are not well constrained by theory, and the latitudinal structure of the trends exhibits considerable variability from data set to data set and—to a lesser extent—model to model[30] (Fig. 3). Trends in the stratospheric mass circulation are difficult both to detect and to predict.

In contrast, trends in global-mean stratospheric temperature are relatively simple to constrain quantitatively. The influence of the stratospheric mass circulation on temperature trends is negligible in the global-mean temperature because the regions of upward and downward motion average out. Thus trends in global-mean stratospheric temperatures are driven almost entirely by the radiative effects of changes in stratospheric composition, primarily increases in carbon dioxide and changes in ozone concentrations, but also changes in the concentrations of water vapour, aerosols and other trace gases. If the NOAA SSU data are correct, then both the CCMVal2 and CMIP5 models are presumably missing key changes in stratospheric composition.

What might give rise to the discrepancies between observed and simulated global-mean stratospheric temperatures highlighted here? The long-term increases in stratospheric concentrations of carbon dioxide are probably well constrained by observations and in models owing to the fact that carbon dioxide is largely inert and thus well mixed in the atmosphere. Simulations of stratospheric water vapour trends and their effects on temperature vary considerably from model to model[18]. But the effects on temperature of stratospheric water vapour trends are much more important in the lower stratosphere than they are in the middle and upper stratosphere[2]. Therefore, uncertainties in simulated stratospheric water vapour trends may contribute to the discrepancies between simulated and observed temperature trends in the lower stratosphere, but they seem unlikely to contribute significantly to the discrepancies in the middle and upper stratosphere. Trace gases such as nitrous oxide, methane and fluorinated greenhouse gases are not believed to have had a pronounced effect on trends in the middle and upper stratosphere[2,18]. And multiple observational sources suggest that the overall trends in stratospheric aerosols were very small over the SSU period (about 1979–2005)[31]. Hence, the pronounced discrepancies between simulated and observed global-mean stratospheric temperature trends are most probably due to one of the following two possibilities.

(1) **The observations may be in error.** The MSU channel 4 temperature record is robust from one data set to the next, so we consider it to be unlikely that uncertainties in the MSU channel 4 data can account for the discrepancies between modelled and observed lower stratospheric temperatures shown here. Uncertainties in middle and upper stratospheric temperatures derived from the SSU instrument are much larger.

(2) **The simulated ozone trends may be in error.** The observed and simulated global-mean ozone trends are very similar in both the middle and upper stratosphere[26]. We therefore consider it to be unlikely that the differences between modelled and observed temperature trends in the middle and upper stratosphere can be explained by differences in ozone trends at these altitudes. Uncertainties in ozone depletion in the lower stratosphere[32] may help to account for the discrepancies between modelled and observed trends in temperatures there.

How might the climate community resolve the mysteries raised by the new SSU data? First, the methodology used to generate the original Met Office SSU data remains undocumented and so the climate community are unable to explain the large discrepancies between the original Met Office and NOAA SSU products highlighted here. The World Climate Research Programme's Stratospheric Temperature Trends Assessment Panel (of which several authors of this study are members) has encouraged the scientists who generated the original Met Office data set to publish the methodology, but they are now retired. We encourage the Met Office to allocate resources towards the recovery and publication of as much of the original SSU metadata as possible.

Second, the SSU data should be processed by at least one additional independent research group. Similar controversies regarding surface and tropospheric temperature changes over the past few decades have motivated tests of the reproducibility of trend estimates. Other key data sources are now routinely vetted, processed and published by a number of research organizations: scientists have produced at least three independent MSU temperature products, five independent radiosonde temperature products' and five global surface temperature products for climate research (see discussion in refs 4 and 7). The SSU data have been processed by only two independent research groups, and published by only one.

Third, the amplitudes of the observed stratospheric ozone depletion should be critically assessed in all available data sources, discrepancies between simulated and observed variability in stratospheric ozone should continue to be explored, and remotely sensed observations used to estimate stratospheric ozone depletion should be processed by independent research groups (for example, as done for MSU channel 4 temperatures). The World Meteorological Organization and International Ozone Commission are supporting an effort to critically evaluate ozone profile trends based on remotely sensed and *in situ* measurements. It remains to be seen whether revised estimates of stratospheric ozone depletion are large enough to account for the discrepancies between observed and modelled stratosphere temperature trends highlighted here.

Finally, to avoid a continuation of the current perplexing and frustrating situation, it is imperative that stratospheric altitudes are included in future climate reference data networks. The Global Climate Observing System (GCOS)—a project overseen by the World Meteorological Organization, the United Nations Environment Program, and other international bodies—is currently developing a 'reference' upper-air network consisting of around 30–40 ground-based stations that will be used to constrain the numerous atmospheric observations used in climate research (the GCOS Reference Upper-Air Network; GRUAN[33]). Other than these incipient GRUAN observations, there are currently no reference temperature data at stratospheric altitudes. The GRUAN effort is essential for assessing future stratospheric climate change without the ambiguities we currently face.

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